The contribution of normal, dim and dwarf galaxies to the local luminosity density

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ABSTRACT

From the Hubble Deep Field catalog presented in Driver et al. (1998) we derive the local ($0.3 < z < 0.5$) *bivariate brightness distribution* (BBD) of field galaxies within a 326 Mpc^3 *volume-limited* sample. The sample contains 47 galaxies which uniformally sample the underlying galaxy population within the specified redshift, magnitude and surface brightness limits ($0.3 < z < 0.5$, $-21.3 < M_B < -13.7$ mags, $18.0 < \mu_B < 24.55$ mags/$\square''$). We conclude: (i) A luminosity-surface brightness relation exists for both the field and cluster galaxy populations, $M_B \approx [(1.5 \pm 0.2)\mu_e - (50 \pm 2)]$, (ii) Luminous low surface brightness galaxies account for $< 10\%$ of the L_* population, (iii) Low luminosity low surface brightness galaxies outnumber Hubble types by a factor of ~ 1.4, however their space density is **not** sufficient to explain the faint blue excess either by themselves or as faded remnants. In terms of the local luminosity density and galaxy dynamical mass budget, normal galaxies (*i.e.* Hubble tuning fork) contribute 88% and 72% respectively. This compares to 7% and 12% for dim galaxies and 5% and 16% for dwarf galaxies (within the above specified limits).

Subject headings: galaxies: luminosity function, mass function — galaxies: evolution — cosmology: observations — galaxies: fundamental parameters — galaxies: dwarf

1. Introduction

The Hubble Deep Field (Williams 1996) and the many publications which have stemmed from these data are primarily associated with the studies of faint galaxies (Driver et al. 1998; Ferguson & Babul 1998), galaxy morphology (Abraham et al. 1996; Odewahn et al. 1996), the evolution of luminous galaxies (Abraham et al. 1999) and the high redshift Universe in general. However the Hubble Deep Field (HDF) also provides us with the deepest insight of the local universe probing into both the low surface brightness fog as well as the *intrinsically* faint Universe. Since the original formulation of surface brightness selection effects and their potential impact on galaxy catalogs (Disney 1976), the topic of low surface brightness galaxies has developed into a thriving area of scientific research (see Impey & Bothun 1997, for a recent review). However uncertainty still remains as to whether such systems represent a major or minor component of

the galaxy population or more fundamentally the mass budget. This uncertainty arises because of the difficulty in firstly establishing a complete catalog of galaxies and secondly in obtaining the necessary distance measurements. Similarly the space density of intrinsically faint, or dwarf, galaxies is equally uncertain partly because they are predominantly of low surface brightness, but more fundamentally because the volumes over which dwarf galaxies have been surveyed are small (c.f. Driver & Phillipps 1996). In general the space density of galaxies is poorly constrained. and can be quantified as a factor of ~ 2 at L_* rising to a factor of ~ 100 at $0.01L_*$, and indeterminate faint wards (c.f. Zucca et al. 1997 v's Lin et al. 1996).

What is required is an objective perspective of the entire local space density of galaxies. That is a *volume*-limited sample over a wide and well controlled range of surface brightness and intrinsic luminosity. Here we show how such a sample can be constructed from the Hubble Deep Field utilizing photometric redshifts and quantify the contribution to the local luminosity density from normal, dim and dwarf galaxies. We adopt a standard flat cosmology ($\Omega_o = 1, \Lambda = 0$), with $H_o = 75$km s^{-1}Mpc^{-1} throughout.

2. Constructing a Volume-limited sample

In Driver et al. (1998) we combined the photometric redshift catalog of Fernández-Soto, Lanzetta & Yahil (1998) with the morphological catalog of Odewahn et al. (1996). This catalog has now been extended a further magnitude to $I < 27$ (now containing 675 galaxies), and updated to include quantitative measurements of the apparent half-light radii (see Odewahn et al. 1996). Figure 1 shows a representation of this extended catalog by plotting each galaxy according to its redshift (x-axis) and its K-corrected absolute magnitude (y-axis). These galaxies form a distribution which is bounded by the two appropriate apparent magnitude limits ($B(F450W) > 19.5$ and $I(F814W) < 27$). The reliability of photometric redshifts ($\Delta z \approx 0.1$) are discussed in Hogg et al. (1998). In Figure 1 a horizontal line represents a sight-line across the past 10 Gyrs for a narrow absolute magnitude range and a vertical line represents a *volume*-limited sample at a specified redshift (within well defined magnitude and surface brightness limits). From Fig. 1 a *volume*-limited sample is *i.e.* any rectangle which lies within the apparent magnitude limits. As we wish to explore the *local* galaxy population we shall concentrate on the low-z range generously redefined to $0.3 < z < 0.5$ (326 Mpc^3).

The final sample contains 47 galaxies. Figure 2 shows these galaxies plotted according to their mean absolute surface brightness and their absolute B-band magnitude. The selection lines shown on Fig. 2 are discussed in detail in §3. Note that our chosen surface brightness measure is the intrinsic mean surface brightnesses (μ_e) within the effective radius. The effective radius is derived from the measured azimuthally averaged half-light radii within the 25 I(F814W) mags per sq arcsecond isophote (r_e). Hence:

$$\mu_e = m_b + 2.5log_{10}(2) + 2.5log_{10}(\pi r_e^2) - 10log_{10}(1+z) - K(z) \quad (1)$$

The measured r_e values are taken from Odewahn et al. (1996) and the measured magnitudes and fitted K-corrections from Fernández-Soto, Lanzetta & Yahil (1998). This measurement of the surface brightness includes the bulge component which explains why the values appear to be brighter than the more conventional extrapolated central surface brightness - typically 21.7 mags per sq arcsec for early-type disk systems (Freeman 1970). Our motivation for using this measure of surface brightness is that no assumption of

3. Selection Limits

Having arbitrarily defined our redshift limits our absolute magnitude limits are automatically set by the combination of these with the apparent magnitude constraints ($B > 19.5; I < 27$) as follows:

$$M_B^{Upper} = m_B^{bright} - D_{z_{LOW}} - K_{z_{LOW}} \tag{2}$$
$$M_B^{Lower} = m_I^{faint} - D_{z_{HIGH}} - K_{z_{HIGH}} + (B - I) \tag{3}$$

Adopting $\Omega_{Total} = 1, \Lambda = 0$ and $H_o = 75\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$, the distance moduli are: $D_{0.3} = 40.5$, $D_{0.5} = 41.7$. To be conservative we adopt a K-correction suitable for a blue galaxy ($K_{0.3} = 0.3$) at our upper limit and also a blue galaxy ($K_{0.5} = 0.5$, $(B - I) = 1.8$) for our lower limit (Driver et al. 1994). This results in a *conservative* absolute magnitude range for completeness of: $-21.3 < M_B < -13.7$ - galaxies just outside this range can be detected but not over the entire 326 Mpc^3 volume. The shaded regions on Fig. 1 show these selection limits over all redshift intervals using a simplistic K-correction of K(z)=z. Note that the paucity of objects in the shaded region lends credence to both the above magnitude limits and the reliability of photometric redshifts.

The upper surface brightness limit is defined by the point at which a galaxy with the lowest possible apparent magnitude is contained within a single resolution element (more luminous galaxies within a single pixel will have higher surface brightness measures). For any absolute magnitude this will occur at the highest possible redshift (*i.e.* z=0.5) hence the limit can be defined as follows:

$$\mu_e^{Min} < M_B + D_{z_{HIGH}} + 2.5log_{10}(2) + 2.5log_{10}(\pi(r_e^{Min})^2) - 10log_{10}(1 + z_{HIGH}) \tag{4}$$

Where $D_{0.5}$ is the distance modulus (41.7) and r_e^{Min} is the resolution limit of the drizzled WFPC2 data ($r_e^{Max} = 0.04''$). Conversely the dimmest measurable surface brightness is defined by two limits. Firstly the fundamental isophotal detection limit at z=0.5, i.e.:

$$\mu_{limit}^{B450W} = \mu_{Iso}^{I814W} - 10log_{10}(1 + z_{HIGH}) - K_{z_{HIGH}} + (B - I) \tag{5}$$

and secondly by the maximum size at which an object can be detected, r_e^{Max} (typically fixed by the f.o.v. or size of any smoothing filter). This results in a selection line as follows:

$$\mu_e^{Max} > M_B + D_{z_{LOW}} + 2.5log10(2) + 2.5log(\pi(r_e^{Max})^2) - 10log_{10}(1 + z_{LOW}) \tag{6}$$

Where $D_{0.3} = 40.5$, and $r_e^{Max} = 10''$.

4. The Observed Bivariate Brightness Distribution

On Figure 2 we map those objects with $0.3 < z < 0.5$ onto an effective absolute surface brightness versus absolute magnitude plane. Those galaxies which lie within these selection boundaries represent the first *volume limited* census of the local galaxy population, *i.e.* these 47 galaxies are a statistically uniform sample of the underlying galaxy population within these limits. In particular it surveys a larger volume for dim and dwarf galaxies than most [1] existing magnitude limited redshift surveys (c.f. Driver & Phillipps 1996), and extending to luminosities comparable to the brighter Local Group dwarfs (c.f. Mateo 1998).

(1) **The majority of galaxies lie along a magnitude-surface brightness relation ($M_B \approx [(1.5 \pm 0.2)\mu_e - (50 \pm 2)]$).** This is in very close agreement with that found for galaxies in the Virgo cluster ($M_B \propto 1.6\mu_o - K$, Binggeli 1993). This trend has recently been predicted from theoretical arguments (Dalcanton et al. 1998) and through simulations of hierarchical merging (e.g. Jiménez et al. 1998; Mo et al. 1998). Further work is required to allow direct comparisons between simulations - which in essence predict the mass versus angular momentum of the dark matter haloes - and observations - which determine the luminosity and surface brightness of the stellar population. It seems logical to suppose that the greater a galaxies angular momentum the lower will be its surface brightness. Coupled with the accepted correlation between luminosity and mass, the BBD may represent a key connection between easily obtained observables and fundamental physical properties.

(2) **Low surface brightness luminous galaxies are relatively rare.** Low surface brightness galaxies have been postulated as a potentially grossly overlooked population (Disney 1976), within which might be contained a substantial integrated mass (Impey & Bothun 1997). No such objects were identified in our 326Mpc^3 volume. Unless our volume is unrepresentative the constraint is that luminous LSBGs (with $-21.3 < M_B < -18$ and $21.7 < \mu_e < 24.55$) are rare accounting for $< 10\%$ of the total L_* population. Note that 21.7 mags per sq arcsec is adopted as the high/low surface brightness boundary, as this implies a system with a negligible bulge component. However we note that galaxies are known, such as Malin1 (Bothun et al. 1987), which would not be detectable even in the HDF sight-line (due to both size and dimness).

(3) **At** $0.3 < z < 0.5$ **Dwarf galaxies are more numerous than giant galaxies**. Dwarf galaxies have been proposed as an explanation to the faint blue galaxy problem (see Ellis 1997, for a review) either by postulating a dense inert population of dwarfs (e.g. Driver et al. 1994) or through the recent fading of starbursting dwarfs to low surface brightness limits (e.g. Driver & Phillipps 1996; Babul & Ferguson 1996). In these two cases it is required locally for the dwarf-to-giant ratio to be ~ 50 if non-evolving (Driver et al. 1994) or a factor of ~ 5 if evolving (Phillipps & Driver 1995). The level of dwarfs seen in Fig. 1 (dwarf-to-giant ratio = 1.4) does not support either of these

[1] Only the LCRS (c.f. Lin et al. 1996) surveys a larger volume for galaxies with $M_B = -14$ (~ 700Mpc^3), where peculiar motions and survey incompleteness become significant due to the extreme closeness of the volume.

scenarios. This suggests that while dwarf galaxies may contribute in part to the faint blue excess they cannot be wholly responsible and a luminous population at higher redshift is also required (see also Driver et al. 1998). This dwarf-to-giant ratio is consistent with recent measures of the global luminosity function (e.g. Zucca et al. 1997), but inconsistent with the high dwarf-to-giant ratio of ~ 4 seen locally over the same absolute magnitude range (Karachentsev et al. 1999). This may be due to the local volume being non-representative or alternatively due to the greater scrutiny of the local environment (i.e. even lower optical surface brightness limits and radio surveys).

5. The Luminosity Density of the Universe

Having constructed a volume-limited sample it is trivial to derive the luminosity-density of the Universe, *i.e.* $j_B = \sum_{\mu_e=24.55}^{\mu_e=18} \sum_{M_B=-13.7}^{M_B=-21.3} 10^{0.4(M_{\odot}-M)} L_{\odot}$. This is a fundamental parameter useful for cosmological purposes and can be combined with the maximum observed mass-to-light ratio to obtain an *upper limit* to Ω_{Matter} (Carlberg 1997). Table 1 shows the results for our HDF volume-limited sample for all galaxies and also for subdivisions into giant (i.e. classical Hubble types), dim (i.e. LSBG disks) and dwarf systems. Of interest, is that the value itself is typically 3-4 times larger than that obtained from local surveys. This is most likely a statistical variation due to the small volume surveyed. However it may also be a reiteration of a classic problem of faint galaxy models, namely the steepness of the local galaxy counts (Driver et al. 1995; Marzke et al. 1998; Driver et al. 1995). Finally we can now address the long standing question as to the cosmological importance of low surface brightness and dwarf galaxies. Table 1 shows the luminosity density for subregions of the BBD which fit with our definitions of high surface brightness giants, low surface brightness giants and dwarf galaxies as indicated. Adopting an invariant mass-to-light ratio these values for the luminosity density would correspond directly to the percentage contribution to the galaxy mass density. However studies of both low surface brightness galaxies and dwarf galaxies suggest mass-to-light ratios typically increase towards both lower luminosity and lower surface brightnesses (de Blok et al. 1996; Karachentsev et al. 1999). More work is require in this area, however for the moment we consider the results presented by Zwaan (1995) based on observed Tully-Fisher relationships for low surface brightness galaxies of $\frac{M}{L} \propto \Sigma_o^{-\frac{1}{2}}$. We normalize this expression to the data of de Blok et al. (1996), to give an $\frac{M}{L} = 3$ for normal high surface brightness disks ($-21.3 < M_B < -13.7, \mu_e = 20.0$). The percentages based on these numbers are also shown in the final two columns of Table 1 which finally reflects the local cosmological significance of high surface brightness, low surface brightness and dwarf galaxies. To first order we see that high surface brightness galaxies dominate both the luminosity density and to a slightly lesser extent the mass budget. Nevertheless the contribution from both low surface brightness and dwarf galaxies is non-negligible and may be partly responsible for the variation seen in measures of the local luminosity function (c.f. §1).

6. Conclusions

We have demonstrated that a *volume*-limited sample over a wide and well defined magnitude and surface-brightness range can be constructed from the Hubble Deep Field and hence any deep, high resolution multi-color imaging survey. The volume-limited data has been mapped onto the first bivariate brightness distribution (BBD) for field galaxies. A clear result is a strong luminosity-surface brightness relationship similar to that reported in the Virgo cluster. We advocate the possible potential of the BBD as a meeting point between simulations and observations by noting the logical connections between surface brightness & angular momentum and luminosity & mass. If shown to be true the BBD may represent a new and powerful tool with which to trace galaxy evolution and environmental dependencies. More specifically the measured BBD over the 326 Mpc^3 volume and valid for $0.3 < z < 0.5$, $-21.3 < M_B < -13.7$, $18.0 < \mu_B < 24.55$ shows no luminous low surface brightness galaxies and only a modest dwarf population. Hence we conclude that no evidence is seen for a "missing" local population (within the above specified limits). In terms of the luminosity density and mass density we conclude that locally high surface brightness giant galaxies dominate both the luminosity density (88 %) and the galaxy contribution to the mass density of the local universe (72 %). If a hierarchical model of galaxy formation is correct then these contributions will decrease with redshift. Such data will soon be attainable with the *Hubble Space Telescope* Advance Camera and the *New Generation Hubble Space Telescope*.

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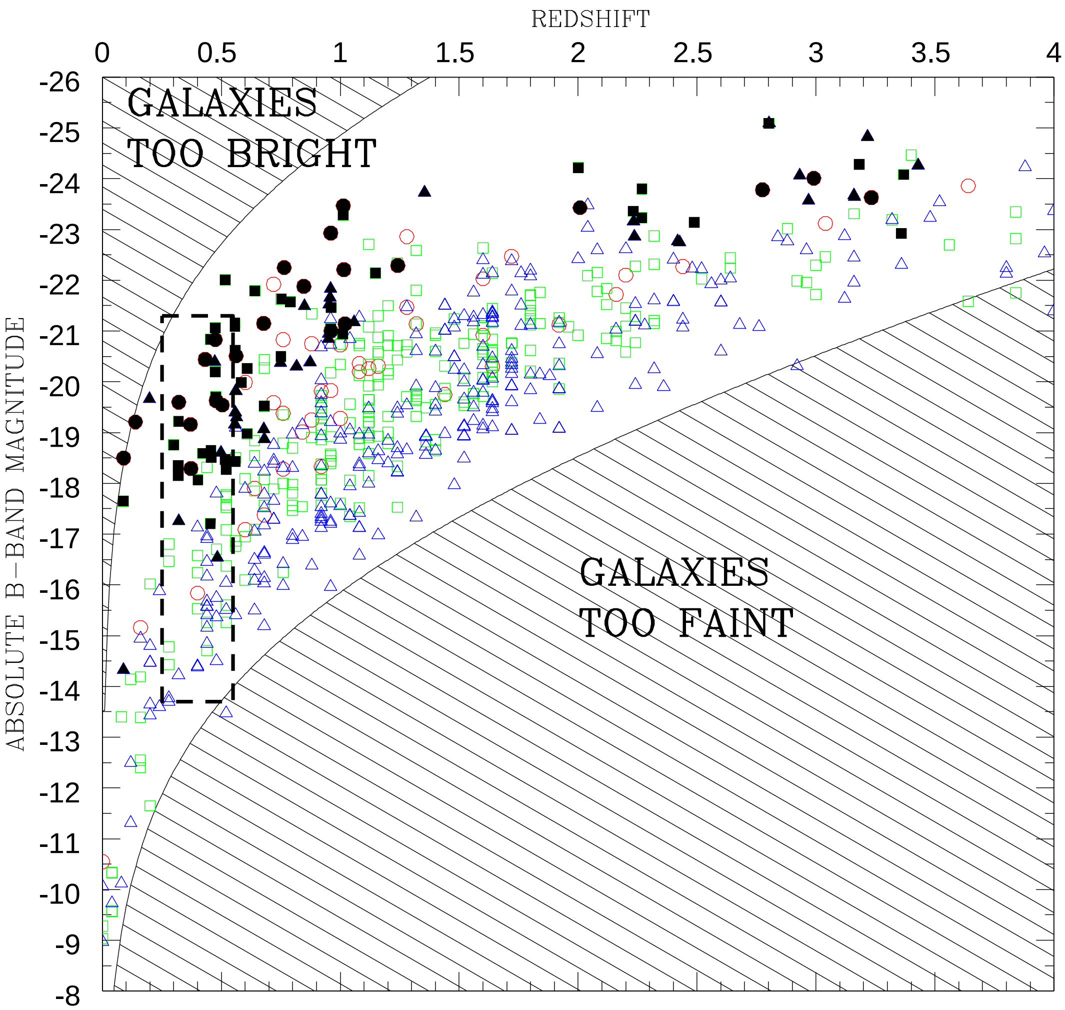
Fig. 1.— Galaxies with $I < 27$ from the Hubble Deep Field positioned according to their absolute magnitude (M_B) and redshift (z). The shaded region indicates the magnitude selection boundaries as defined in §3.1. Symbols are: ellipticals (circles), spirals (asteriks) and irregulars (triangles). Open symbols indicate photometric redshifts and solid symbole spectroscopic redshifts.

Fig. 2.— The bivariate brightness distribution for the HDF volume limited sample and including various selection lines as indicated by the dashed lines. Symbols indicate morphological classifications: E/S0 (open circles), Sabcs (asterisks), Sd/Irr (triangles)

Table 1. The contribution of various galaxy generalizations to the luminosity density and the dynamical galaxy mass budget within the limits shown.

Galaxy Class	M_B (mags)	μ_e (mags/$\square''$)	j ($10^8 L_\odot \mathrm{Mpc}^{-3}$)	(%)	$\rho_M^{Galaxies}$ (10^{-28}kg m^{-3})	(%)
All	$-21.3 < M_B < -13.7$	$18.0 < \mu_e < 24.55$	8.2 ± 1.2	100%	2.5 ± 0.3	100%
Normal	$-21.3 < M_B < -18$	$18.0 < \mu_e < 21.7$	7.2 ± 1.8	88%	1.8 ± 0.4	72%
Dim	$-12.3 < M_B < -18$	$21.7 < \mu_e < 24.55$	0.6 ± 0.3	7%	0.3 ± 0.15	12%
Dwarf	$-18 < M_B < -13.7$	$18.0 < \mu_e < 24.55$	0.4 ± 0.1	5 %	0.4 ± 0.1	16%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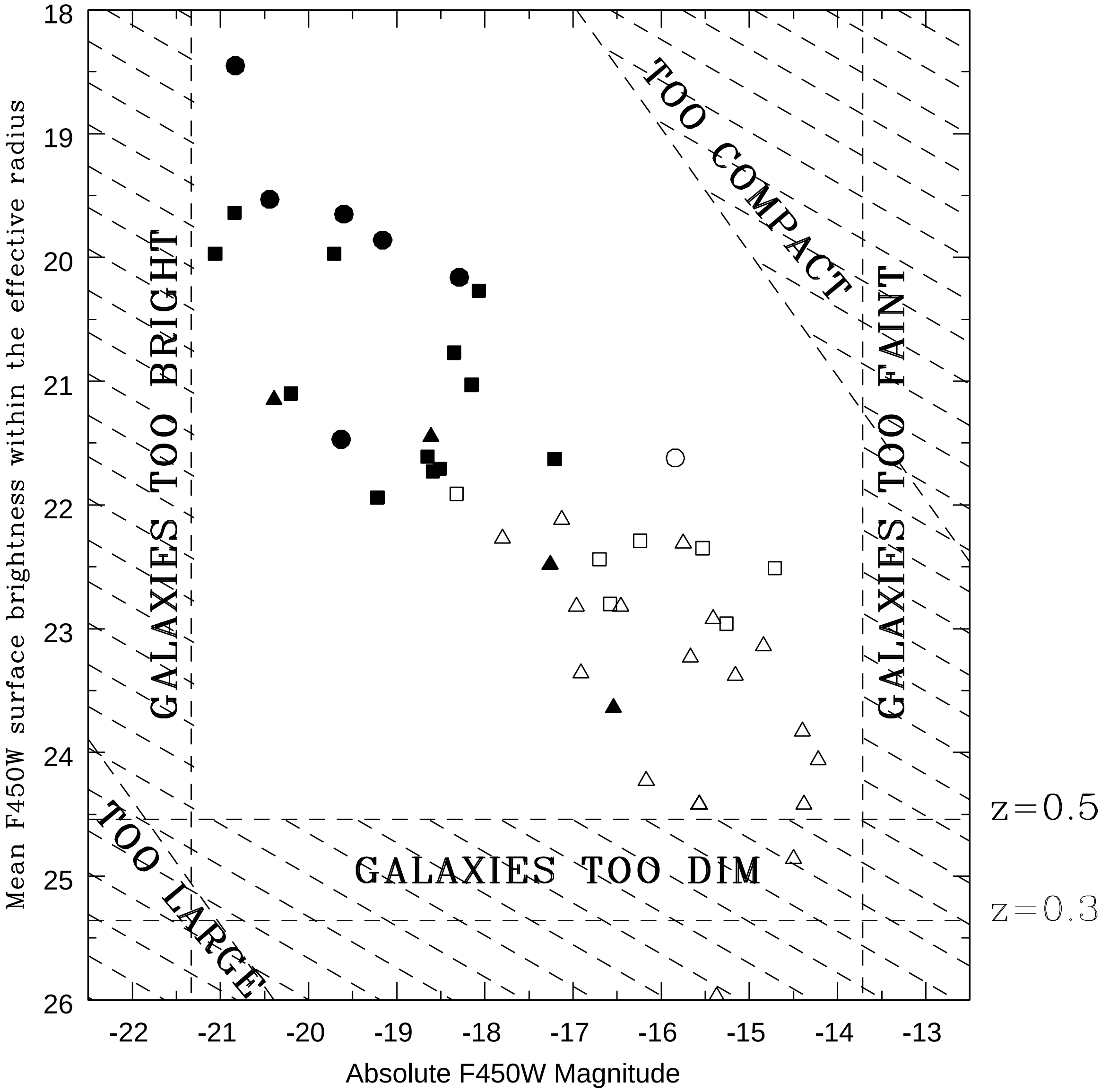

Mean F450W surface brightness within the effective radius
Absolute F450W Magnitude
18
19
20
21
22
23
24
25
26
-22
-21
-20
-19
-18
-17
-16
-15
-14
-13
GALAXIES TOO BRIGHT
TOO COMPACT
GALAXIES TOO FAINT
GALAXIES TOO DIM
TOO LARGE
z=0.5
z=0.3